P4-Based Emulation of LoWPAN and RPL Networks for Aviation Telemetry and Communication

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***Abstract*—This demonstration showcases the benefits of P4 programmability to improve the efficiency and adaptability of IEEE 802.15.4-based LoWPANs using the RPL protocol. By leveraging P4, the platform enables dynamic packet processing and real-time telemetry, essential for optimizing routing decisions and enhancing network reliability in mission-critical environments. To validate these capabilities, we present an emulation platform that integrates P4-programmable BMv2 switches with IEEE 802.15.4 LoWPAN and RPL, creating a realistic and flexible environment for simulating wireless sensor networks in aviation scenarios. The platform supports dynamic sensor management, in-band telemetry, and fine-grained control over network behavior, enabling the study of routing dynamics, bottlenecks, and load-balancing strategies. Preliminary results confirm the effectiveness of this approach in replicating low-power wireless communication, highlighting its potential as a powerful and cost-effective testbed for next-generation IoT and aviation systems.**

***Index Terms*—P4, Network Emulator, LoWPAN, Aviation**

I. Introduction

The growing demands of industrial Internet of Things (IoT) applications necessitate networks that are not only flexible and programmable but also highly reliable in dynamic and mission-critical environments. In the aviation industry, efforts are underway to enhance the efficiency of modern aircraft. Driven by safety and environmental policies, as well as pursuit of competitive advantages, the industry is exploring ways to reduce the weight of aircraft wiring [1]. By minimizing cabling, manufacturers can lower fuel consumption, reduce carbon emissions, and significantly cut operational costs-leading to both economic and environmental benefits.

In this context, Low-Power Wireless Personal Area Network (LoWPAN) appear as a promising network in industrial applications for sensors communication, including aviation [2]. Integrating with Ethernet can enhance reliability or even replace it in scenarios that demand low power and high resilience. A prominent example of this evolution in aviation is the concept of Wireless Avionics Intra-Communications (WAIC), which enables wireless communication between subsystems within a single aircraft. Defined and supported by the International Telecommunication Union (ITU) [3], WAIC systems aim to reduce the weight and complexity associated with traditional wired networks, while maintaining the stringent safety, latency, and reliability requirements of avionics environments, as defined by the aircraft wireless protocol safety and certification code described in specific aviation standards, especially the DO-326A/ED-202A family.

However, ensuring redundancy and safety in large-scale LoWPAN remains a challenge across critical domains, such as aircraft, where multiple systems, including flight control, engine management, fuel monitoring, cabin pressurization, climate control, and landing gear, must operate simultaneously. To further complicate matters, not all sensors contribute equally to system operation.

Accordingly to the primary standards for airborne systems certification (RTCA DO-178C and RTCA DO-254), sensors vary in criticality depending on their function [1]. Flight Control and Navigation Sensors (e.g., gyroscopes, accelerometers), Inertial and Positioning Systems (e.g., GPS), and Engine and Propulsion Sensors (e.g., temperature, vibration, fuel flow) are DAL A systems, vital for real-time maneuvering, requiring ultra-low latency and high reliability. In contrast, Terrain Awareness and Warning System (e.g., altimeters, GPS) are DAL B systems, providing essential telemetry but can tolerate modest delays. Non-critical systems, such as cabin environmental sensors, are DAL level E systems that contribute to passenger comfort and typically have the lowest communication priority. This heterogeneous system requires a network that dynamically adapts to the role of each sensor.

By combining P4 programmability with adaptive RPL metrics, our architecture supports context-aware routing and resource allocation based on operational importance of different types of sensor data. To manage this, adaptive RPL (IPv6 Routing Protocol for Low Power and Lossy Networks) [4] metrics are used to dynamically structure the network based on the priority of different types of sensor data. For example, while structural integrity sensors are important, they may have lower priority than flight control sensors, allowing the network

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to optimize load balancing, alleviate congestion, and minimize latency in critical communications.

RPL is well-suited for constructing redundant topologies with alternative data paths. However, restoring connectivity after critical sensor failures remains a major challenge. In this way, dynamic telemetry-based metrics can be used to detect failures and enable real-time network reconfiguration. Fortunately, RPL facilitates the deployment of multiple DoDAGs (Destination Oriented Directed Acyclic Graphs), ensuring that critical sensors maintain connections to multiple parent nodes, aligning with avionics reliability standards that typically require at least Level 2 redundancy. Furthermore, fast local repair mechanisms enhance network reliability by allowing neighboring nodes to seamlessly take over data retransmission, minimizing disruptions while ensure continuous operation.

To achieve this level of optimization, RPL requires innovative solutions that address key challenges such as scalability, energy constraints, frequent topology changes, security, and maintaining Quality of Service (QoS) [5]–[7]. Programming Protocol-independent Packet Processors (P4) [8], a high-level language designed for the data plane, provides a powerful solution that, when combined with RPL, offers unparalleled control over packet processing and forwarding. This integration improves network adaptability, efficiency, and resilience. The programmability of P4 can further enhance scalability by optimizing the handling of RPL control messages and routing functions, boosting energy efficiency through tailored forwarding rules, and enabling real-time adjustments to accommodate dynamic network conditions

By leveraging the flexibility of P4, we can significantly enhance the performance and efficiency of RPL-based LoWPANs in aviation applications. Integrating P4 with RPL presents a promising approach to addressing the challenges inherent in low-power, lossy networks. To explore this potential, we introduce a novel emulation platform that integrates P4-programmable BMv2 switches with IEEE 802.15.4-based LoWPAN and RPL, providing a flexible and scalable environment for simulating mission-critical aviation scenarios.

II. System Design

The emulated platform, P4LoWPAN, extends a fork of Containernet (https://github.com/ramonfontes/containernet) to emulate programmable sensors with P4 support, enabling the testing of novel routing and optimization strategies. P4LoWPAN provides fine-grained control over the network by integrating essential management tools such as iwpan, ip, and RPL. At the userspace level, nl802154 facilitates IEEE 802.15.4 device management in Linux, leveraging Netlink (nl) sockets for seamless communication between userspace utilities and kernel components.

A key enhancement of the proposed architecture lies in the integration of In-band Network Telemetry (INT), which enables real-time and fine-grained monitoring of network performance directly within the data plane. As illustrated in Figure 2, the architecture builds upon the Mininet-WPAN framework and introduces a critical innovation: the deployment of sensor nodes, including the DoDAG Root, as Docker containers with P4-enabled capabilities. This design significantly enhances flexibility, scalability, and programmability, positioning the platform as a powerful foundation for dynamic IoT network experimentation and research.

Mininet-WPAN extends the Mininet-WiFi emulator [9] to support IEEE 802.15.4-based networks through integration with the Linux mac802154 wireless device driver. Within this framework, each emulated sensor node (e.g., *sensor1-wpan0*, *sensor2-wpan0*, ..., *sensorN-wpan0*) operates inside an isolated Docker container, each equipped with a virtual WPAN interface (wpan0). Mininet-WPAN offers support for essential network management tools such as iwpan, ip, and RPL, enabling fine-grained control and dynamic configuration of network behavior.

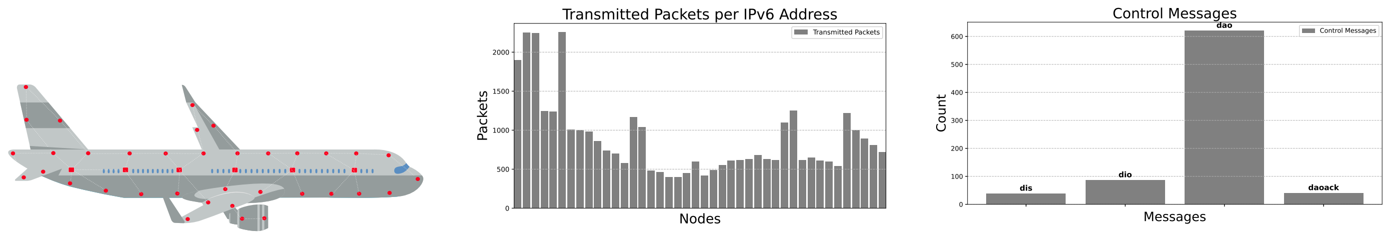
At the userspace level, the nl802154 subsystem manages IEEE 802.15.4 interfaces via Netlink sockets, enabling communication between user-level utilities and kernel components. In the kernel space, the mac802154 module implements the MAC layer for IEEE 802.15.4, serving as the core controller for WPAN interface operations. Additionally, the mac802154_hwsim module functions as a hardware simulator, enabling the creation of virtual WPAN interfaces. This emulation capability allows for the deployment of complex wireless scenarios without the need for physical devices, which is critical for testing and development in wireless sensor network (WSN) research.

The proposed P4LoWPAN architecture is composed of three main components:

- **RPL-INT Collector Node** - responsible for aggregating and analyzing telemetry data, providing insights into the network's performance and operational health;
- **P4-enabled DoDAG Root** - acts as the central node for routing orchestration, network coordination, and telemetry management, leveraging P4 to process and forward data intelligently;
- **Sensor Nodes** - represent the IoT endpoints, each capable of generating and embedding INT metadata into packets for real-time performance analysis.

By combining P4 programmability with INT, P4LoWPAN delivers a flexible and high-performance solution for IoT environments. This integration facilitates enhanced observability, automated control, and fine-tuned optimization of low-power and lossy networks (LLNs). As a result, P4LoWPAN establishes itself as a robust and extensible platform for advancing research in next-generation IoT systems and intelligent network infrastructure.

To enhance the understanding of this demonstration's results, we implemented a GUI that visually represents: (i) the organization of sensors based on their connections within an aircraft, (ii) statistics on transmitted packets, (iii) the distribution of RPL control messages, and (iv) real-time detection of sensors in the aircraft as RPL control messages are exchanged.



(a) Aircraft-Installed Sensors (b) Transmitted Packets. (c) Control Messages.

Fig. 1: (a) Aircraft-Installed Sensors, (b) Statistics of packets, and (c) control messages received by the DoDAG Root.

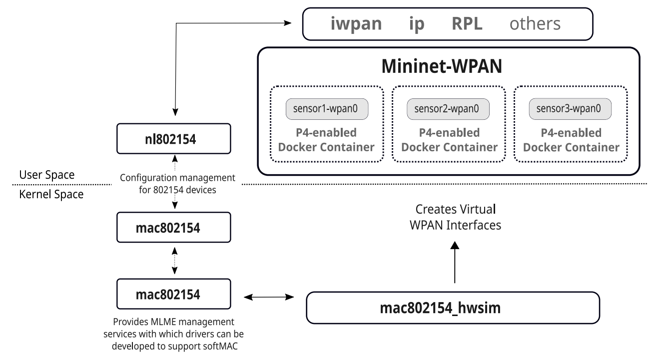


Fig. 2: Architecture and Components.

III. Demonstration

Figure 1a illustrates sensors installed in an aircraft, as visualized using the RPL DoDAG Visualization tool, which is a GUI developed to map the network topology. For simplicity purpose, we emulated 42 LoWPAN sensors on a Ubuntu system running Kernel version 6.5.0-1025. In this sense, preliminary results demonstrate that our emulation platform effectively replicates IEEE 802.15.4 networks, integrating the RPL protocol and BMv2 switches.

Demonstration steps: We let the user interact with the network emulator and monitor its status on GUI. We then demonstrate how the P4 code is used with IEEE 802.15.4 protocol to build the network topology through RPL control messages filtering, while also enabling the extraction of statistics on transmitted and received data (Figure 1b), as well as RPL control messages (Figure 1c).

Preliminary results: Demonstrations show that when a data packet is transmitted, it ascends through the network hierarchy toward the DoDAG root node. The root node determines a viable path to the destination and forwards the packet, facilitating communication between nodes and maintaining connectivity across the network.

Results further confirm that, as expected, parent nodes with a higher number of child nodes handle a greater volume of data traffic toward the DoDAG root, emphasizing the hierarchical structure of the network. This insight is particularly relevant for aviation applications, where reliable and efficient sensor communication is critical for real-time telemetry and flight operations.

By leveraging P4 in the IoT domain with dynamic metrics like INT, we can efficiently identify traffic bottlenecks in real time. For instance, by analyzing transmitted packets, we can accurately measure data flow patterns, detect congestion points, and optimize routing decisions based on actual network conditions. This capability forms the foundation for implementing advanced redundancy techniques in future work, enhancing network reliability and scalability as the system grows. Such optimizations are essential in aviation environments, where ensuring low-latency, high-reliability communication can enhance aircraft monitoring, fault detection, and overall efficiency.

IV. Conclusion

This demonstration highlighted the potential of P4 programmability to enhance the efficiency and adaptability of IEEE 802.15.4-based LoWPAN using RPL. By enabling dynamic packet processing and real-time telemetry, our approach enables the possibility of improving routing performance while also reducing packet forwarding overhead, optimizing network efficiency and reliability. P4 provides finer control over data flow, enabling better scalability, energy efficiency, adaptability, security, and QoS. These capabilities lay the foundation for future research to unlock P4's full potential within RPL, optimizing network performance across diverse applications. As future work, we plan to integrate XDP/eBPF to assess performance, enhance intelligent packet processing, and further extend the system's capabilities.

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